acoustic wave 20Hz — 20KHz

Chapter Five

ULTRASONIC MEASUREMENT SYSTEMS

Range of ultrasonic

Ultrasound refers to sound waves at frequencies higher than the range of the human ear, i.e. at frequencies greater than about 18 kHz. Ultrasonic waves obey the same basic laws of wave motion as lower frequency sound waves; they have, however, the following advantages:

$\lambda = \frac{c}{F}$

(1) Higher frequency waves have shorter wavelengths; this means that diffraction or bending around an obstacle of given dimensions is correspondingly reduced. It is therefore easier to direct and focus a beam of ultrasound.

metal

(2) Ultrasonic waves can pass easily through the metal walls of pipes and vessels. This means that the entire measurement system can be mounted completely external to the fluid, i.e. is non-destructive. This is extremely important with hostile fluids, such as those with corrosive, radioactive, explosive or flammable properties. There is also no possibility of blockage occurring with dirty fluids or slurries.

(3) Ultrasound can be launched into and propagated through biological tissue, making it useful for medical applications.

(4) The silence of ultrasound means that it has important military applications.

TX, RX

This chapter studies ultrasonic transmitters and receivers, and the principles of transmission, and examines a range of ultrasonic measurement systems.

1. Basic ultrasonic transmission link

This forms the basis of any ultrasonic measurement system and is shown in Figure 1. It consists of an ultrasonic transmitter, the transmission medium and an ultrasonic receiver. The most commonly used devices for ultrasonic transmitters and receivers are piezoelectric sensing elements.

The piezoelectric effect is reversible, i.e. mechanical energy can be converted into electrical energy and electrical energy into mechanical. The ultrasonic transmitter uses the inverse piezoelectric effect; if a sinusoidal voltage $V_s \sin \omega t$ is

applied to the transmitting crystal, then the crystal undergoes a corresponding sinusoidal deformation x.

This vibration of the crystal is transmitted to the particles at the beginning of the medium, and these are set in sinusoidal motion, causing other particles to vibrate, until eventually the disturbance is transmitted to the other end of the medium.

These sinusoidal particle displacements set up an accompanying sinusoidal pressure or stress in the medium.

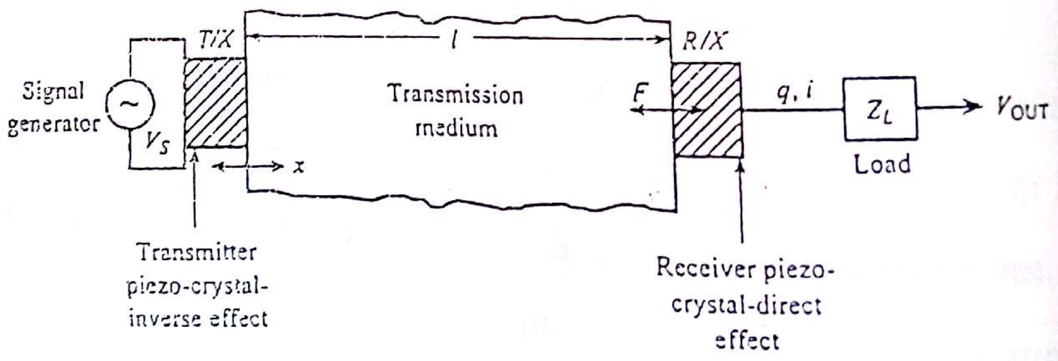

Figure 1: Basic ultrasonic transmission link

This is detected by the ultrasonic receiver, which is simply a force sensor using the direct piezoelectric effect. The fluctuating

$$\frac{\lambda'}{\lambda} = \frac{\text{velocity of waves relative to source}}{\text{normal wave velocity}} \qquad [17]$$

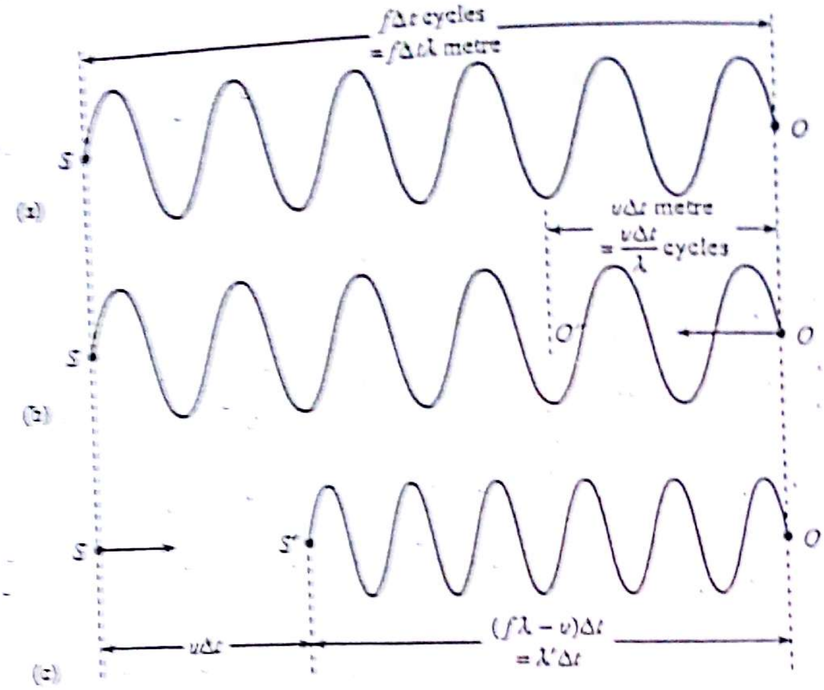

Figure 5: Doppler Effect.

4. Examples of ultrasonic measurement systems

4.1 Pulse echo system

Figure 6(a) shows a typical system. A piezoelectric crystal acting as a transmitter/ receiver is attached to medium 1; the characteristic impedances of media 1 and 2 are substantially different. When the crystal acts as a transmitter, an oscillator

giving a sinusoidal voltage at radio frequency f is connected to the crystal for a time T_w using switch A. Thus a pulse of ultrasound of width T_w enters medium 1 and most of the pulse energy is reflected at the boundary of medium 1 with medium 2. The reflected pulse returns to the crystal at a time T_T after the outgoing pulse. Since T_T is the time for the 'round trip' of distance $2l$ then:

$$T_T = \frac{2l}{c} \qquad [18]$$

Where l is the distance of the interface from the crystal and c is the velocity of sound in medium 1. The crystal now acts as a receiver and converts the reflected pulse into a voltage pulse. Switch B is now closed so that the pulse passes to the echo signal conditioning circuit where it is amplified, rectified and 'squared up' using a Schmitt trigger.

Figure 6(b) shows the idealised outgoing and reflected pulse waveforms. These pulse waveforms pass to a logic circuit which detects the leading edge of the outgoing pulse and that of the first reflected pulse; the resulting output is a pulse signal

which is in the "1" state during the transit time T_T. This is used to control a counter which also receives clock pulses at frequency f from the signal generator. The total count N during the "on" time is therefore $N=fT_T$. This is transferred to a microcontroller using a parallel digital signal. The computer calculates T_T from N and uses equation [18] with a known value of c to find l. The measurement is complicated by the creation of multiple reflections or 'echoes'. Part of the first reflected pulse is reflected at the boundary of medium 1 and the crystal, and reflected again at the boundary of media 1 and 2 to give a second reflected pulse.

The process is repeated many times, the amplitude of the reflected pulses dying away due to attenuation losses in medium 1 and reflection losses at the boundaries. Figure 6(b) shows these multiple reflected pulses. The following conditions should be obeyed by the pulse signal:

a) The pulse width T_w should be large compared with the period $1/f$ of the sound wave; this ensures that there are many cycles, *i.e.* sufficient energy, in each pulse:

$$T_w > 1/f \quad [19]$$

b) The transit time T_T should be large compared with the pulse width T_w to avoid interference between outgoing and reflected pulses:

$$T_T > T_w \quad [20]$$

c) The repetition time T_R between successive outgoing pulses should be large compared with transit time T_T; this ensures that all reflections, following one outgoing pulse, are attenuated before the next enters the material:

$$T_R > T_T \quad [21]$$

Because of the large difference in characteristic impedance between most solids and air, this method can be used for thickness measurement. Pulse reflection techniques are also commonly used for the detection of flaws in metals. Here frequency f is chosen so that the sound wavelength is small compared with the size of defects it is desired to detect.

An important application of pulse reflection techniques is in the "imaging" of areas of the human body. Figure 7(a) shows,

in simplified form, the various layers of tissue. The characteristic impedance of these layers will be different: for example, the impedance of bone is around 0.8×10^7 whereas that of soft biological tissue is around 0.15×10^7. A piezoelectric transducer is placed on a matching layer. This minimises internal reflections at the boundary and the problem of multiple echoes.

Figure 7(b) shows the CRT trace obtained when the system of Figure 6 is used with the layer system of Figure 7(a). The three reflected pulses correspond to reflections at the epidermis/dermis, dermis/fat and fat/bone boundaries respectively; the time intervals between successive reflected pulses are proportional to the thickness of each layer.

This trace, referred to as an A-scan display, is rather difficult to interpret; a more realistic image is obtained using a 2-dimentional image (B-scan) display. Here the transducer is connected to two displacement sensors which measure transducer *x* and *y* position coordinates on the body surface.

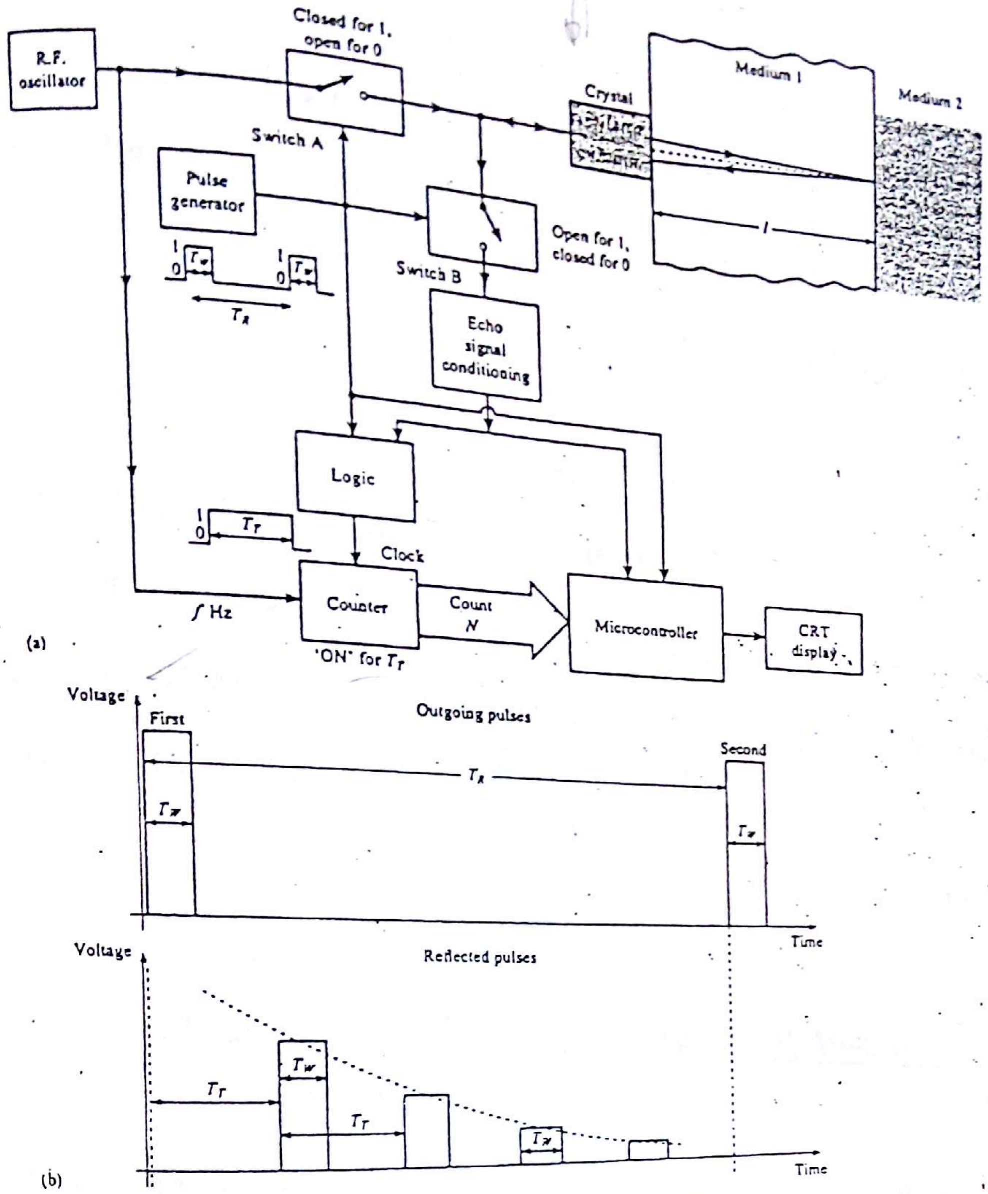

Figure 6: Pulse echo Technique.

The output voltage of the x sensor is applied to the X plates of the CRT and a voltage proportional to time, *i.e.* distance z travelled through the body, is applied to the F plates. The brightness of the image on the screen is proportional to the transducer output voltage so that a bright spot corresponds to a

reflected pulse.

By keeping the transducer y-coordinate fixed and adjusting the x-coordinate, an image of the body in the x-z plane is built up and stored (Figure 7(c)). Thus the B-scan images a "slice" through the body, normal to the surface.

Another alternative is the C-scan display; this is an image of the body in the x-y plane, i.e. a slice parallel to the surface of the body. This is obtained by applying x sensor output voltage to the CRO X plates and y sensor output voltage to the Y plates and using Z modulation. Figure 8 shows a C-scan display of a human foetus.

4.2 *Time-of-flight diffraction (TOFD) system*

Conventional ultrasonic techniques such as pulse echo measure the reflected pulse transit time and the signal amplitude to locate and size flaws. In pulse echo, the amplitude of the reflected pulse is influenced by parameters other than the dimensions of the reflector (such as the orientation of the flaw transparency and surface roughness); therefore, pulse-echo may not always provide reliable or accurate sizing information.